PATTERNS AND CONTROLS OF GULLY GROWTH ALONG THE SHORELINE OF LAKE HURON

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ABSTRACT

An empirical approach was used to examine the morphology and behaviour of gullies along the eastern shoreline of Lake Huron, Canada. Gully and watershed dimensions and percentage vegetation cover of a sample of 44 gullies were measured from aerial photographs between 1930 and 1992. Gullies with larger watersheds had higher area growth rates. Larger gullies continue to expand over time while small gullies are more likely to become stable. Growth rates increased between 1955 and 1978 because of increased snowfall, extreme flow events, the extension of municipal drains, and the use of subsurface drainage. After 1970, efforts to rehabilitate gullies using drain pipes and check dams contributed to a decrease in gully growth rates. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Gullies are ephemeral drainage channels which are incised into thick sediment deposits or bedrock (Gregory and Walling, 1973). Advancing gully heads cause damage to roads and structures, and may result in the loss of agricultural, residential and recreational land (Ireland *et al*., 1939; Seginer, 1966). Resource managers and residential planners need to relate the expansion rates of gullies to other measurable variables to explain and estimate future gully morphology and behaviour. An understanding of gully morphology therefore allows for the planning strategies which may reduce land use conflicts.

Most analyses of gully growth are empirical in approach (Table I). Gully expansion, usually measured as an increase in area and/or length over time, is commonly evaluated from successive aerial photographs or maps (Beer and Johnson, 1963; Thompson, 1964; Seginer, 1966; Stocking, 1980). Gully expansion is then linked to a variety of factors including drainage basin area, gully dimension parameters, indices of surface runoff and precipitation, antecedent precipitation, soil moisture, and indices of piping (Beer and Johnson, 1963; Thompson, 1964; Seginer, 1966; Piest *et al*., 1975; Stocking, 1980). Odermerho and Sada (1984) analysed urban characteristics including population density, roof type, and land use along with physical characteristics. In most studies, a power function was the best fit for the relationship between growth rates and other variables (Beer and Johnson, 1963; Thompson, 1964).

A series of large gullies incised into the Algonquin Bluff along the eastern shoreline of Lake Huron (Figure 1), Ontario, is causing damage to roads and loss of land. The area is mainly agricultural and is dominated by row crops such as corn and beans, which are highly susceptible to soil erosion (Wischmeier and Smith, 1978; Dickinson *et al*., 1989). In the past 20 years, there has been a growth in the use of land adjacent to the bluff for cottages. A few large subdivisions for seasonal residential use have been planned in this area as the demand for this type of property grows. A number of gullies are included in the development areas, but little is known about gully morphology and behaviour. The objectives of this paper are (i) to determine area and length expansion of gullies, (ii) to relate growth rates to gully geometry and watershed variables, and (iii) to examine growth rate trends and discuss possible factors affecting them.

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Table I. Parameters used to examine gully growth

Parameters	Source*										
	A	B	C	D	E	F	G	H	I	J	K
Basin area	×	×	×	×	×			×	×		
Basin length	×		×					×			
Basin height	×			×							
Channel slope				×				×	×		
Total precip.		×	×	×			×	×			
Antecedent precip.						×		×			
Runoff			×			×					
Headcut advance rate				×	×						
Areal growth rate of gully		×	×								
Clay content (%)				×					×		×
Soil moisture										×	×
Soil shear strength						×					×
Soil bulk density											×
Ground water level changes											
Season						×					
Vegetation cover (%)						×	×	×	×		
Index of piping							×	×			
Rainfall interception (%)							×	×			
Population density							×	×			
Agricultural use									×		

* Sources: A, Seginer (1966), Israel; B, USDA (1966), eastern USA; C, Beer and Johnson (1963), Iowa, USA; D, Thompson (1964), USA; E, Faulkner (1974), Alberta, Canada; F, Piest *et al.* (1975), Missouri Valley, USA; G, Elwell and Stocking (1975), Rhodesia; H, Stocking (1980), Rhodesia; I, Odemerho and Sada (1984), Nigeria; J, Egboka and Nankwor (1985), Nigeria; K, Poesen and Govers (1990), Belgium

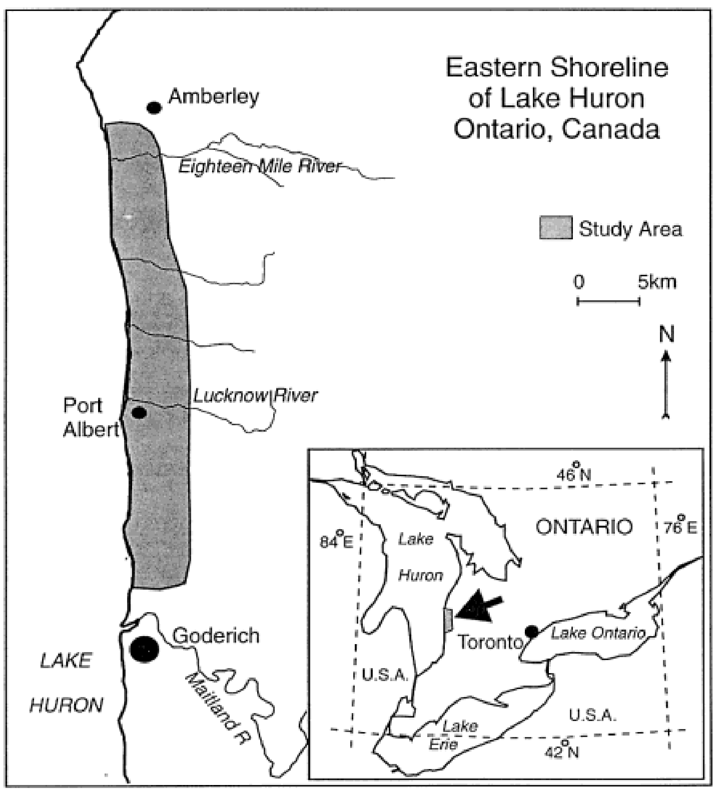


Figure 1. Map of study area

STUDY AREA

The climate of the study area is temperate, modified by the lake effect. Mean annual precipitation at Lucknow (Figure 1) is 1014 mm, 700 mm of which falls as rain (Canada Atmospheric Environment Service, 1930–1990). In winter, most precipitation is snowfall, which is released rapidly in the spring. Peak annual discharges and largest sediment loads in local streams occur during the spring melt (Dickinson, 1972; Sangal and Kallio, 1977).

Surficial deposits in the region are primarily clays of glaciolacustrine and glacial origin (Chapman and Putnam, 1966). The sediment has a coarse, blocky structure and is firm when dry but plastic when wet (Hoffman *et al*., 1952). Internal drainage is very slow and perched water tables can result during prolonged precipitation events (Hoffman *et al*., 1952). The lowering of lake levels during the Holocene resulted in a flat land surface fronted by the steep, eroding, 23 m high Algonquin Buff (Chapman and Putnam, 1966).

Shortly after settlement began in the region, agricultural drainage ditches provided knickpoints from which gully incision was initiated (Burkard and Kostaschuk, 1995). Modern gullies range from 20 to 1500 m in length, generally have a linear shape, and are oriented perpendicular to the shoreline. Vegetation on the gully slopes includes coniferous and deciduous trees, shrubs and perennial grasses. Rill networks, indicating surface erosion, are evident on all unvegetated slope surfaces during the spring, summer and autumn. Mass wasting occurs most frequently during the spring snowmelt when the slopes are saturated, and may also appear following storm events of long duration. The most common mass wasting processes are shallow mud flows and rotational slumps. Mass wasting was evident on some vegetated slopes but was more frequent on slopes without vegetation.

The expansion of gully length in about one-third of the gullies has been anthropogenically restricted by measures such as cement check dams, reinforcement of headcuts with rocks and debris, or redirection of drainage by drain pipes. Even though growth in length is limited, many gullies expand laterally, resulting in a continued increase in area (Burkard and Kostaschuk, 1995).

METHODS

Aerial photographs from 1930, 1955, 1966, 1978, 1983 and 1992 (e.g. Figure 2) were digitized and gully characteristics (Figure 3) measured for a sample of 44 gullies. The scales of the aerial photographs ranged from 1:10 000 to 1:16 000. Radial distortion was minimized by using control points and digitizing gullies closest to the centre of the aerial photograph (Alberts, 1992). However, individual digitized points could be in error up to 3 m from the actual points because of error inherent in the digitizing software.

Gully area is defined as the outer boundary of the gully banks (Figure 3). The boundaries of some gullies were difficult to define because of concealment by vegetation, but stereographic viewing and field reconnaissance minimized this problem. Length is the along-channel distance of the gully stream channel from head to mouth (Figure 3). Watershed area is the area that drains into channels which flow into the gully through the headcut and over the side slopes (Figure 3). Watershed areas were determined from surface drainage apparent on 1978 aerial photographs (1:10 000) and it is assumed that this area does not change significantly over time. Other studies have defined watershed area as the contributing area above the headcut which decreases as the gully erodes upstream (Beer and Johnson, 1963; Seginer, 1966). However, this ignores the impact of runoff entering the gully at the top of the side slopes, which can cause a significant amount of erosion (Blong, 1985).

We chose to examine area and length growth rates in our investigation. Length growth rates were examined because headcut advance is an essential process in gully erosion, increasing slope instability and sidewall erosion (Foster, 1982). Area growth rates are an important measure of gully expansion in many environments because as much as half of the sediment produced by gully erosion is derived from gully sidewalls (Blong *et al*., 1982; Blong, 1985). Growth rates were calculated by measuring the difference in gully area or length over the time period between successive aerial photographs, then dividing this by the number of years between photographs.

Surficial deposits are similar for all the gullies so soil type and soil texture were not examined in our analysis. Only two meteorological stations exist near the study area (Lucknow and Goderich) so there were insufficient

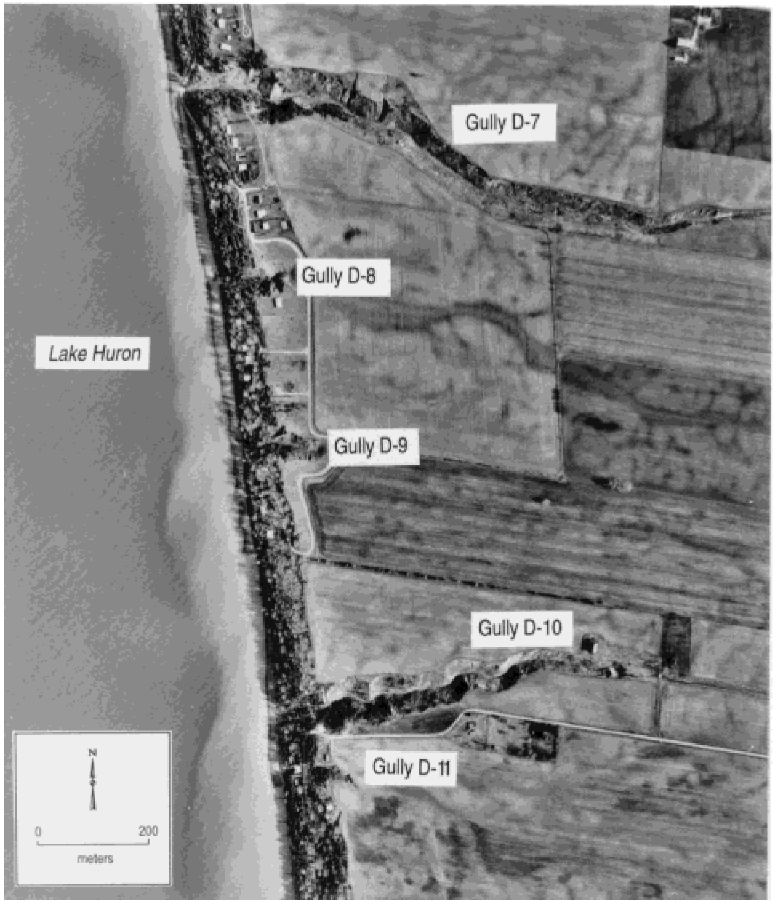


Figure 2. Aerial photograph of gullies (1983)

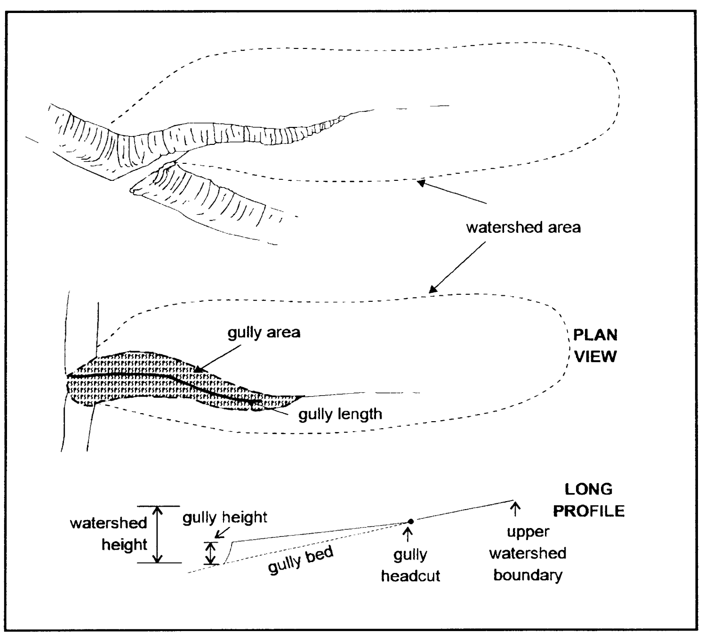


Figure 3. Diagram of gully dimensions

Table II. Summary of gully data

	Mean*	Minimum	Maximum	Sk†	S‡
1930					
Area (m^2)	11 098·25	466·8	6106·0	1·50	11 699·69
Length (m)	317·29	50·7	1016·8	1·03	256·68
1955					
Area (m^2)	16 205·45	1196·3	58 015·0	1·40	16 149·98
Length (m)	359·58	65·8	1038·3	0·87	273·67
1966					
Area (m^2)	19 151·93	1336·8	66 268·0	1·30	18 639·42
Length (m)	399·60	56·8	1053·8	0·77	306·97
1978					
Area (m^2)	22 190·21	2375·3	84 064·0	1·50	22 822·23
Length (m)	422·02	72·0	1454·5	1·04	360·96
1983					
Area (m^2)	23 258·19	2447·0	89 549·0	1·50	23 775·88
Length (m)	451·16	78·3	1471·1	1·06	366·96
1992					
Area (m^2)	25 222·74	2484·5	101 310·0	1·54	25 662·02
Length (m)	460·20	78·3	1478·5	1·06	358·93
Watershed					
Area (m^2)	2 342 301	18 700	12 165 000	1·57	2 777 299

* Sample mean
† Skewness
‡ Standard deviation

Table III. Area and length growth rates between 1930 and 1992

	Mean*	Minimum	Maximum	Sk†	S‡
Area growth rates ($m^2 a^{-1}$)					
1930–55	204·29	11·30	823·44	1·46	194·27
1955–66	271·99	9·71	972·54	1·07	281·33
1966–78	253·19	0	1784·50	2·65	410·43
1978–83	213·60	0	1097·00	1·71	243·54
1983–92	218·28	0	1306·78	2·41	247·11
1930–92	277·81	17·77	980·16	1·65	230·72
Length growth rates ($m a^{-1}$)					
1930–55	1·69	0	7·41	1·58	1·80
1955–66	3·64	0	31·99	2·97	6·67
1966–78	3·54	0	33·39	2·98	6·43
1978–83	1·80	0	16·54	2·64	3·42
1983–92	0·97	0	8·62	3·45	1·51
1930–92	2·31	0·24	9·45	1·78	2·31

* Sample mean
† Skewness
‡ Standard deviation

data to examine precipitation variation amongst gullies. Since all gullies are located adjacent to the shoreline and the study area is small, spatial variations in precipitation are unlikely to be controlling factors of gully growth over the long term.

RESULTS

Table II summarizes descriptive statistics for gully area and length for each set of aerial photographs. Most data were positively skewed and the skewness increased as the gullies aged. Mean gully length increased by 45 per cent between 1930 and 1992, while mean gully area increased by 127 per cent over the same period (Table III). From 1983 to 1992, 13 gullies had zero length growth and eight expanded by $0{\cdot}5\,m\,a^{-1}$ or less. During the same period, seven gullies had area growth rates of less than $30\,m^2\,a^{-1}$. Fifty-seven per cent of gullies smaller than the mean area in 1992 had length growth rates of $0{\cdot}5\,m\,y^{-1}$ or less, and 21 per cent expanded by less than $30\,m^2\,a^{-1}$.

Table IV. Regression relations of area and length gully growth rates (1930–1992). P is the probability that the result occurred by chance. All the relations are significant at the 99 per cent confidence level

Variables	Equations	R^2	P
Gully area growth, G_A ($m^2 a^{-1}$)			
vs. watershed area D (m^2)	$G_A = 0{\cdot}3996\, D^{0{\cdot}59}$	0·77	0·0001
vs. gully area 1930, A (m^2)	$G_A = 0{\cdot}1382\, A^{0{\cdot}79}$	0·86	0·0001
Gully length growth, G_L ($m a^{-1}$)			
vs. gully length 1930, L (m)	$G_L = 0{\cdot}0271\, L^{0{\cdot}74}$	0·52	0·0001

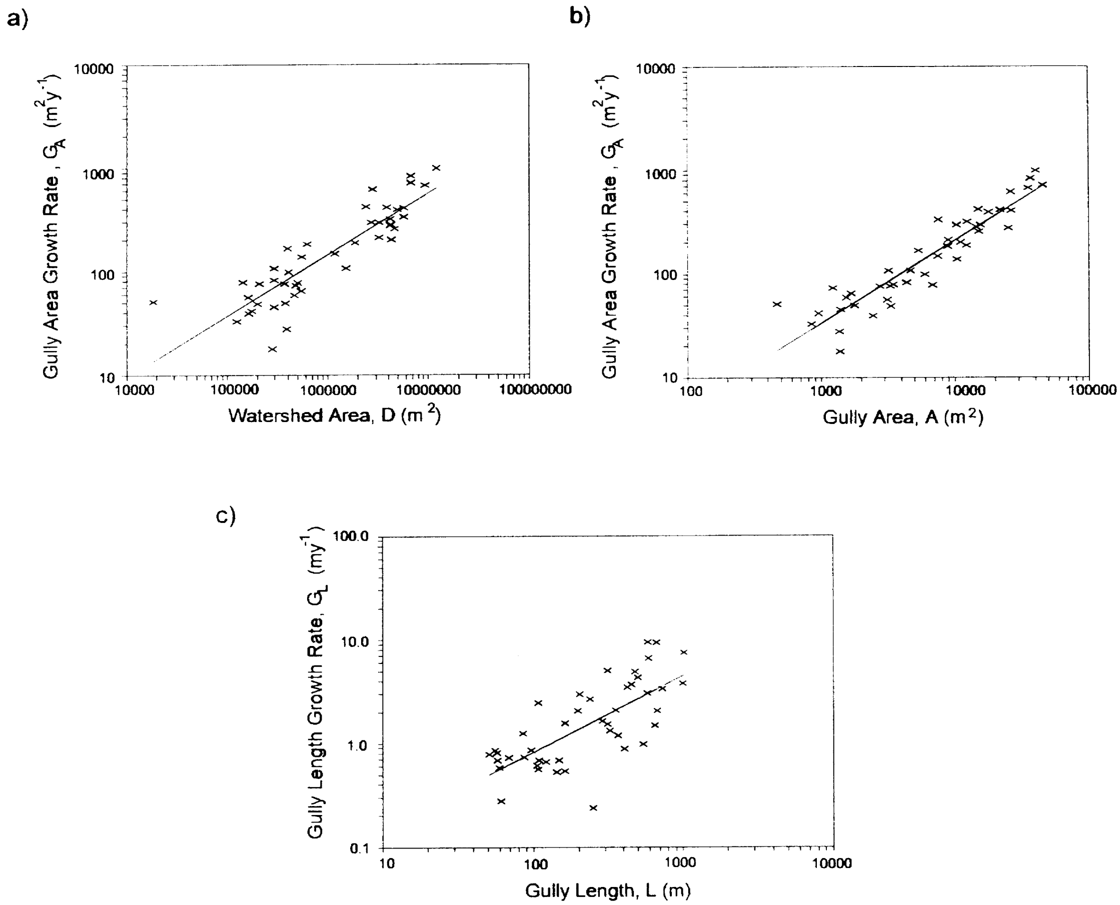


Figure 4. Relations (1930–1992) between gully area growth rate and (a) watershed area and (b) gully area; and (c) between gully length growth rate and gully length. Regression results are summarized on Table IV

Most previous studies found power function relations between gully growth rates and controlling variables. Our data were log-normal, therefore the use of logarithmically transformed data satisfied the least-squares linear regression assumption of normally distributed data. Table IV summarizes regression relations for gully area and length growth for the period 1930–1992. Strong significant power relations were found between growth rates of individual gullies and watershed area and gully area in 1930 (Figure 4a,b). A weaker, but significant power relation also occurred between gully length growth rate and gully length in 1930 (Figure 4c).

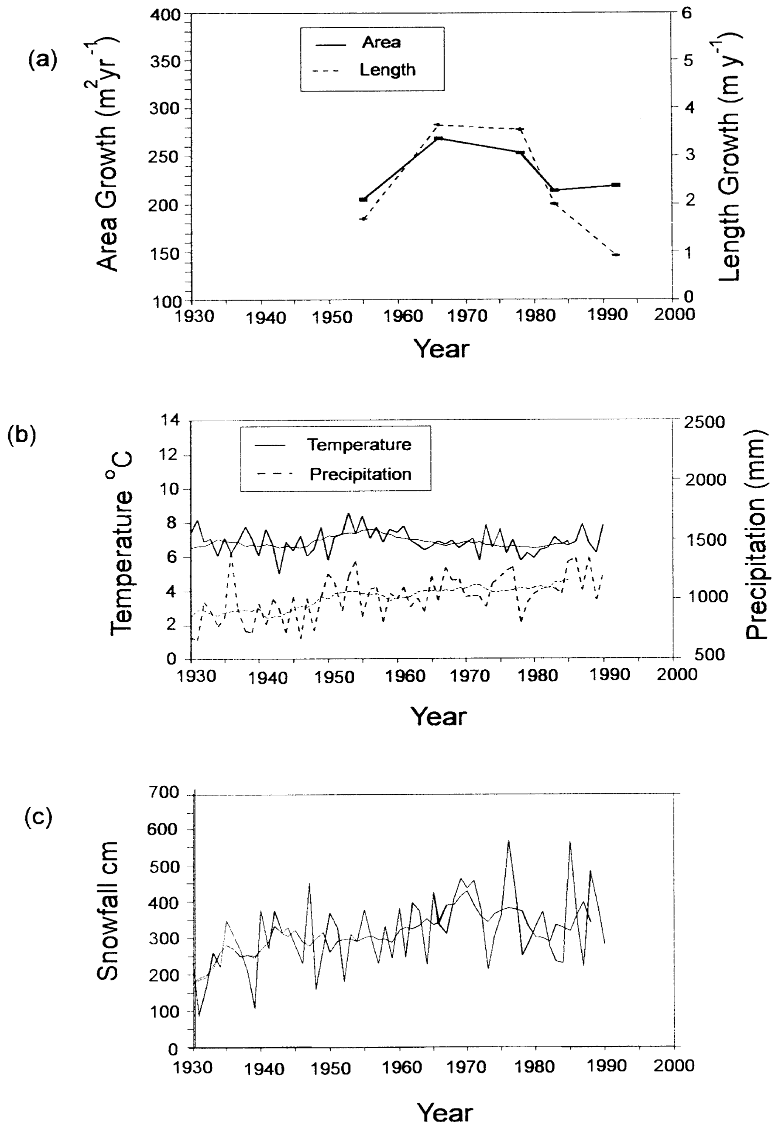


Figure 5. (a) Area and length gully growth rates over time. Climatic changes in mean annual (b) temperature, precipitation, and (c) snowfall, along with ten year running averages

Area and length growth rates increased between 1955 and 1966 and then decreased after 1978 (Figure 5, Table III). Length growth rates continued to decrease after 1983 while area growth rates rose slightly.

DISCUSSION

Regression relations

The factor most commonly related to gully growth rates is watershed area (Table I; Figure 4a). Watershed area explained a significant amount of the variation in gully area growth in this study (Table IV). The value of the exponent in the relation approximates the square root of the watershed area, or the length of slope over which the runoff would have to travel to reach the gully. Longer slope lengths usually connote higher runoff accumulations and greater flow erosivity (Wischmeier and Smith, 1978; Djorovic, 1980). Our results are similar to other studies. Seginer (1966) found an exponent of 0·5 in the relation between gully growth and watershed

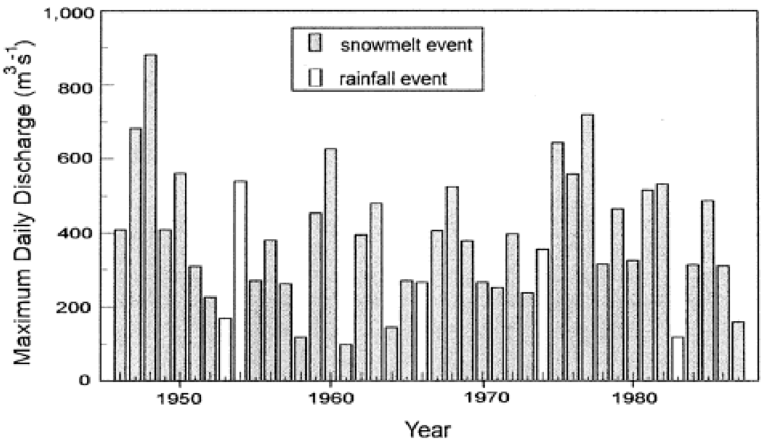


Figure 6. Extreme daily discharges for Maitland River (data from Water Survey of Canada, 1990)

area in Israel and the United States Department of Agriculture (USDA, 1966) standard equation for gully expansion in northeastern USA has an exponent of 0·46. Stocking (1980) formulated power equations with watershed area with exponents ranging from 0·38 to 1·00.

The strong relation between area growth rate and gully size in 1930 indicates that large gullies in our study are growing in area at a faster rate than smaller gullies (Figure 4b), and many small gullies are approaching stability. In other environments, researchers have suggested that there is a finite limit to gully growth. Once a headcut has advanced to a threshold level, the channel slope becomes shallow enough that the gully slopes become vegetated and the gully becomes stable (Heede, 1975; Harvey, 1974, 1992). The large gullies in the Lake Huron environment clearly are not stabilizing but continue to grow in area. Longer gullies are also growing at faster rates than shorter gullies (Figure 4c). Faulkner (1974) suggested that larger gullies will expand by annexing smaller watersheds and continue to grow as flows increase. While larger gullies are capturing watersheds from smaller gullies, the flow discharge to smaller gullies is reduced and the gullies become stable. The slow length growth rates of most small gullies in the Lake Huron area may be a result of this phenomenon.

Growth rate trends

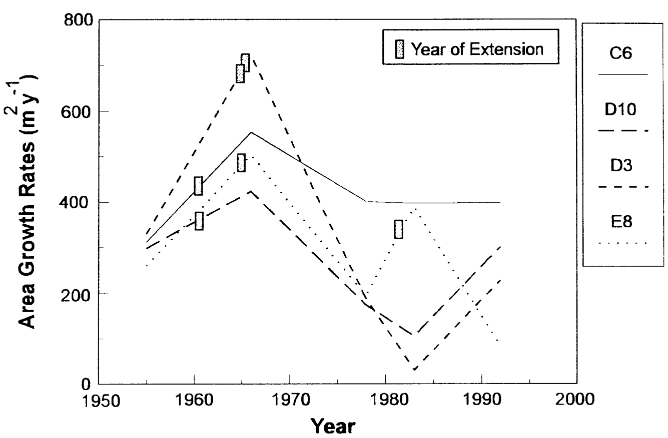
The increases in area and length growth rates between 1955 and 1978 (Figure 5a) are due to climate variations and anthropogenic manipulation of drainage. Mean annual precipitation increased slightly after around 1950 (Figure 5b). More importantly, average annual snowfall amounts increased from 170 cm to 427 cm per year between 1930 and 1970 (Figure 5c). The recorded extreme snowfall amounts were 84·5 cm in 1931 and 568·5 cm in 1976 at Lucknow. Temperatures decreased slightly over the same period, so snowfall accumulations would be less likely to melt during the winter. This would lead to greater accumulations on the ground at the time of the spring thaw (Figure 5b). During the spring thaw, greater snow accumulations contributed to saturated soil conditions, mass wasting, increased overland flow, and gully channel flow discharges. All of these contributed to accelerated gully erosion. From 1946 to 1987, 88 per cent of the maximum daily discharges on the Maitland River occurred in early spring, indicating snowmelt or rain on snow events (Figure 6). Extreme events occurred in 1960, 1975, 1976 and 1977, during the period when the growth rates of many gullies increased (Figure 6). Extreme snowmelt flows occurred in 1947 and 1948, and a major rainstorm flow resulted from Hurrican Hazel in 1954 (Figure 6). These events contributed to gully expansion between 1930 and 1955.

Drainage channels flowing into 12 of the 44 gullies were deepened and extended as municipal drains between 1961 and 1969 (Table V). Further extensions were made to drainage channels of six of the same gullies between 1966 and 1983. Half of the gullies with area growth rates above the mean between 1955 and 1978 had municipal drains (Table V). Figure 7 provides examples of gullies with higher growth rates during the time periods when construction of municipal drain extensions took place. The installation of subsurface drainage in agricultural fields became more common in Ontario after 1965 (Irwin, 1986). During storm events, the increase in artificial drainage would increase the volume and velocity of flows entering the headcuts of gullies, causing gully

Table V. Gullies with municipal drain extensions

Gully	Expansion date	Later expansion	Area growth* ($m^2 a^{-1}$)		Length growth* ($m\,a^{-1}$)	
			1966	1978	1966	1978
C6	1961		**553**	**401**	0·2	1·6
D10	1961		**423**	174	0·6	**3·7**
D7	1962	1972, 1983	256	216	0·2	1·6
D2	1963	1965, 1978	168	169	**3·8**	0·6
D3	1963	1966	**721**	188	**15·9**	0
E8	1963	1973, 1982	**503**	194	1·6	**11·9**
D7	1965	1971	**703**	78	**18·0**	0
D13	1966		156	80	1·0	1·7
D15	1967	1969	184	**362**	1·4	**7·1**
D18	1968		**654**	**1572**	**6·0**	**17·6**
D27	1968		**536**	227	2·9	1·4
E12	1969		**350**	**1784**	1·4	**33·4**
		Mean	268	253	3·6	3·5
		Total no. of gullies > mean	16	9	12	7
		Percentage of municipal drains > mean*	50	44	33	71

* Values in bold are greater than mean value



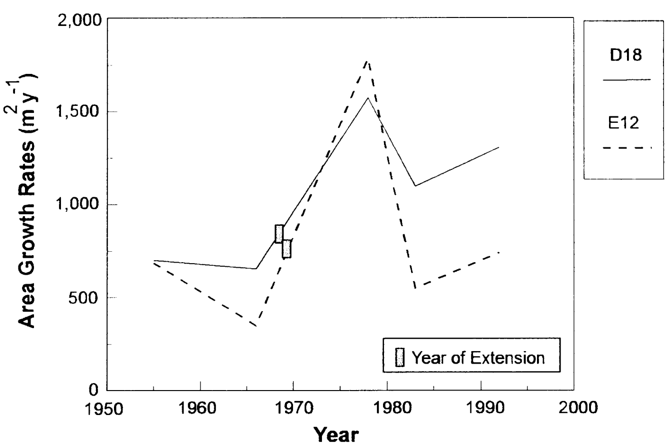


Figure 7. Changes in area growth rates of gullies with municipal drain extensions

expansion. The reduction of gully area and length growth after 1978 may be the result of gully rehabilitation efforts. Since 1970, drain pipes have been installed in the channels of ten small gullies and the gullies have been backfilled and regraded. Cement check dams, to limit headcut advance, were installed in seven of the 44 gullies in the study area during the same period. The headcuts of several gullies have been reinforced with brush, rocks and other debris. The continued decline in gully length growth after 1978 has been largely affected by the restriction of growth by check dams and drain pipe installations.

SUMMARY

Most gullies along the eastern shoreline of Lake Huron expanded between 1930 and 1992. Gullies with higher expansion rates are associated with larger watersheds. Large gullies have high length and area growth rates and are growing rather than stabilizing. About half of the small gullies show little expansion and are likely to become stable. Mean growth rates increased between 1955 and 1978 and then declined. The increase in growth coincided with an increase in snow accumulations and extreme flow events. The extension of farm ditches to create municipal drains and the installation of subsurface drainage in agricultural fields also occurred during this period. The decline in area and, in particular, length growth rates after 1978 was probably a result of gully rehabilitation strategies such as the installation of drain pipes, check dams and the reinforcement of headcuts with brush, rocks and debris.

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